

Ten Years of Super Star Cluster Research

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Abstract.

This conference demonstrated the tremendous progress that has been made in the last decade in our observational and theoretical understanding of compact, young, massive star clusters. One of the Hubble Space Telescope's main achievements was to show that these are young analogues of classical globular clusters and form in profusion in the local universe. They are now recognized as key players in the problems of galaxy evolution and star formation. A major result of the conference is the commonality of the star and cluster formation process across an astonishing range of environments and scales. With the demise of HST, the focus of the field will probably shift to the critical early phases of cluster formation and evolution as revealed with new infrared and radio/mm facilities.

1. Introduction

The title of this conference summary is deliberately chosen. I know many have misgivings about the adjective *super*, which is often associated with things you don't really want. But some of the star clusters we have been discussing are truly extreme and constitute the most concentrated episodes of recent star formation outside the nuclei of galaxies. The *super* appellation is also quite venerable, having been first applied to clusters in the starburst galaxy M82 by van den Bergh in 1971. As for the time scale, intense interest in such clusters was precipitated by a specific discovery with the Hubble Space Telescope—that of a swarm of massive young clusters in the central Perseus Cluster galaxy NGC 1275 by Holtzman et al. (1992) only a little more than 10 years ago.

The phenomenon of super star clusters (SSC's) was not unanticipated before HST. Ground-based observations had revealed a number of barely resolved candidates for young, luminous clusters, mostly in actively star forming galaxies. These included M82-F (O'Connell & Mangano 1978), NGC 2070/R136 in 30 Doradus (Melnick 1985), NGC 1569-A and -B (Arp & Sandage 1985), and the nuclear clusters of NGC 1705 (Melnick, Moles, & Terlevich 1985) and NGC 1140 (Gallagher & Hunter 1987). Remarkably, the clusters ranged in absolute magnitude up to $M_V \sim -15$, 1000 times brighter than typical classical globular clusters. Age estimates ranged from 10 Myr up to about 1 Gyr. Even one merger-remnant system of young clusters (NGC 3597) was known (Lutz 1991).

HST's essential contributions were to show, first, that systems of hundreds to thousands of SSC's could be detected in merger remnants, e.g. in the reigning archetype NGC 4038-9 (Whitmore & Schweizer 1995); and, second, that their

luminosities and sizes were $L_V \sim 10^{6-8} L_{V,\odot}$ and $R_e \lesssim 5$ pc. Combined with their HST-determined colors and ground-based spectroscopic mass measures of $M \sim 10^{5-6} M_\odot$ (e.g. Ho & Filippenko 1996), the properties of the SSC's were exactly what was expected for young analogues of classical globular star clusters.

Thus, HST had demonstrated that *globular cluster formation continues to the present epoch*. This opened an exciting and unexpected new window on a fundamental astrophysical process which had been thought to be confined to protogalaxy conditions and therefore impossible to study in detail in the local universe. Because they were luminous and detectable in a wide variety of environments, super star clusters became recognized as key players in two distinct arenas of the “origins” problems: galaxy evolution and star formation. The result is the wealth of observational and theoretical contributions at this conference.

Observational capabilities were not a specific concern of the conference, but there was a pervasive sense that we were approaching an important crossroads. The last several months have sharpened that realization, and so I first want to discuss the observational livelihood of massive cluster studies.

2. The Demise of HST and New Observational Horizons

The Hubble Space Telescope not only provided the trigger for this field, it is indispensable to it. The majority of important studies of star clusters in the last decade, in our own or other galaxies, have involved use of HST. Although this conference concentrated on young clusters, several talks reminded us that HST also revolutionized the study of classical ($\gtrsim 5$ Gyr old) globular clusters.

The combination of two characteristics of HST was critical to its success in star cluster research: first (of course) is its unprecedented spatial resolution (FWHM $\sim 0.04''$). But equally important is its access to the UV/optical bands ($0.1\text{--}1.0\mu$) that contain the most diagnostics of stellar populations. While the near-infrared ($1\text{--}3\mu$) is a valuable complement in population studies of the nearby universe, it cannot equal the richness and power of the UV/optical region.

The fundamental difficulty we face is that *HST's performance will not be matched or superseded in the foreseeable future* either in space or on the ground.

At our November 2003 meeting, the prospect that HST would be decommissioned in 2010 was sobering enough to impel discussion of how best to use the “little remaining” HST observing time. But in January 2004, NASA cancelled further servicing of HST. Without hardware renewal, the estimated time to a 50% failure probability for scientific operations on HST is only about 30 months. A sobering prospect has become dire, and it is reasonable to assume that the current golden age of star cluster observational science will come to a close by 2007.

There are, nonetheless, other new observational horizons opening up:

Radio, Millimeter, Sub-mm: Given steadily improving sensitivities, these bands offer high-resolution probes of the interstellar medium in and near *younger* SSC's. They are essential for studying cluster formation. The VLA/EVLA/VLBA are mainly important for ionized gas and nonthermal supernova remnants. ALMA

(ca. 2007) offers unprecedented capability to study molecular gas at resolutions of 0.01–0.1".

The Spitzer Space Telescope is a cryogenic 85-cm telescope (3-4 year lifetime) for imaging and spectroscopy in the 3–160 μ bands. With a resolution of only about 2.5" at its shortest wavelengths, Spitzer is not well matched to cluster scales outside our Galaxy. However, it will make unprecedented contributions to our understanding of the dust environments of young cluster-forming systems, the characteristics of heavily obscured clusters, and most importantly the star formation process in our own Galaxy.

Large Ground-Based Telescopes: The essential contribution to date of large (6-m +) ground-based telescopes has been high S/N spectroscopy of SSC's. There are ambitious plans for telescopes in the 15–30-m class. With sophisticated adaptive-optics systems, large telescopes can produce near diffraction-limited performance ($\lesssim 0.05''$) over modest fields of view in the near IR—critical for probes of young, dusty clusters. Because seeing effects become worse at short wavelengths, there is little prospect that AO can match HST resolution below 1 μ . However, optical spectroscopy under the best "natural seeing" of 0.3–0.5" will be quite powerful for studies of cluster dynamics, determination of integrated ages/abundances from spectral synthesis, wind physics, and related problems.

JWST is a 6-m, segmented mirror, near-IR optimized space telescope planned for launch in 2011. It will achieve excellent IR imaging with FWHM $\sim 0.06''$ (2.5 \times better than HST/NICMOS) and free of the very bright atmospheric night-sky IR background. JWST will enable identification of SSC's in local dusty environments and in principle to high redshifts ($z \gtrsim 2$), assuming they are sufficiently isolated from other structures. It will support IR color-magnitude imaging studies of populations in nearer clusters. Its multi-object NIRSPEC will be an exceptionally powerful device for obtaining IR spectroscopy of cluster stars, cluster environments, or multiple SSC's in a 3' field of view. But it is doubtful on both technical and budgetary grounds that JWST will offer HST-quality resolution or sensitivity, and the corresponding leverage on stellar population parameters in the nearby universe, much below 1 μ .

3. Analysis Techniques

Our ability to analyze stellar populations in distant clusters from their integrated light is critically dependent on the availability of high fidelity synthetic models for composite spectra and colors. Fortunately, these are of a rapidly growing sophistication, and over a dozen different model sets are now accessible over the Internet. Model colors must include the effects of emission lines, which are a strong function of metallicity. We heard about the usefulness of certain types of stars as diagnostics in particular age ranges: Wolf-Rayet stars (~ 4 Myr) and asymptotic giant branch stars (~ 100 Myr) in particular. Mechanical energy input from Wolf-Rayet winds, a main determinant of the energy balance of a cluster's interstellar medium and a driver of early gas outflows, is also being thoroughly assessed through improved modeling. An important category needing more work are the red supergiants (~ 10 –20 Myr). These can dominate the near-IR light of clusters toward the end of the critical high ionization stage

of evolution and provide strong CO absorption signatures there, but model sets disagree significantly concerning the details.

We were shown some beautiful hydrodynamic and N-body numerical simulations. These are coming to grips with many aspects of the complexities of star formation within clusters, cluster and starburst winds, and dynamical evolution. It is fair to point to the things left out of such simulations, but it also must be said that the progress in 10 years has been as remarkable as on the observational side.

A major goal of this meeting was to bring theoreticians and observers together, and a basic key to future success is obviously to be relentless in closing the theory/observation loop.

4. Star and Cluster Formation

Perhaps the major result of the conference is the *commonality* of the star and cluster formation process across an astonishing sweep of environments and scales, from the disk of the Milky Way to massive cluster dominant galaxies like NGC 1275. Dozens of studies revealed a number of basic features in common:

- A large fraction (~ 50 – 100%) of all stars form in clusters.
- The mass function for more massive clusters, regardless of age, is a power law $dn(m)/dm \sim m^{-2}$ and is approximately the same everywhere.
- Many systems produce super star clusters—namely, young ($\lesssim 1$ Gyr), compact clusters with sizes comparable to classical globular clusters and masses in the range 10^5 – $10^8 M_\odot$. These number in the thousands in extreme cases. The great majority of such identifications have been made at optical wavelengths in relatively low-extinction environments.
- Radio observations have located ultra-compact H II regions in many environments, most without optical counterparts. These have high densities ($n_e \sim 10^6 \text{ cm}^{-3}$) and pressures ($P/k > 10^8$) and small radii ($\lesssim 5$ pc). They are identified with very young ($\lesssim 1$ Myr) SSC's still in a cocoon phase and powered by dozens to thousands of O stars.
- The total number of clusters, the number of massive clusters, and the maximum cluster luminosity all appear to scale with the total star formation rate, with only a few exceptions (e.g. NGC 1569). This argues for a near-universal cluster formation process, in which the population of SSC's is governed by statistical effects.
- SSC's are predominantly single generation with an internal age spread of $\lesssim 5$ Myr. Exception: the nuclear clusters of late-type disk galaxies, which experience more continuous star formation.
- The spatial structure of SSC's is the same in all environments, and is well fit by the Elson, Fall, & Freeman (1987) profile, which has a power-law envelope without evidence of tidal truncation. The effective radii of SSC's are comparable to those of classical globulars (~ 5 pc). Exception: some

systems, e.g. NGC 1023, have populations of “faint fuzzy” star clusters with $R_e \sim 10\text{--}20$ pc. These may be products of special conditions prevailing in the disks of S0 galaxies.

- The initial mass function for massive ($\gtrsim 5 M_\odot$) stars is a power law with $dn(m)/dm \sim m^{-\alpha}$ and $\alpha \sim 2 \pm 0.3$ in all environments. This is comparable to the Salpeter value ($\alpha = 2.3$).
- The mass function for low-mass stars in SSC’s, as inferred from the handful of kinematic studies to date, is consistent with the Kroupa (2002) function for the solar neighborhood in most cases. This features a flattened power-law ($\alpha \sim 0\text{--}1$ for $m \lesssim 0.5 M_\odot$). Exception: evidence for a possible deficiency of low-mass stars has been found in M82 (2 of 3 clusters), NGC 1705 (nuclear cluster), and NGC 4038-9 (one cluster).
- The mass function of the molecular clouds that are the raw material for cluster formation is a power law with an index ($\alpha \sim 2$) matching that of the massive clusters. Clouds in the Milky Way are often irregular in shape, and most may not be gravitationally bound, unlike the idealizations employed in older generations of models of star formation.

As for the star formation mechanisms that underlie all this activity, it was generally agreed that there is one theme operating on these many scales with perhaps one major variation. Many different aspects of these mechanisms, oriented toward massive cluster formation, were discussed and are summarized next. Numerical simulations illustrated fascinating details of the process, but computational constraints prevented calculations for SSC-sized systems. The largest simulation shown was for $1000 M_\odot$.

- Formation of SSC’s requires a high pressure medium, with $P/k \sim 10^{8-9}$, over 10^4 times higher than the prevailing pressure in the undisturbed ISM of the Milky Way disk. It may be that high pressures must pervade a large volume of $\gtrsim \text{kpc}$ size. We did not discuss at length the galactic-scale gas flows necessary to generate such regions or the sources and transfer of the turbulent energy required for the next step.
- In the models presented, star formation is driven by supersonic turbulence, which must converge on the high pressure zones. Turbulence promotes hierarchical fragmentation of the parent cloud into gravitationally unstable clumps.
- Once started, the time scale for star formation is short, only $\sim 0.1\text{--}1$ Myr.
- Theory predicts an extraordinary formation environment inside a protocluster, characterized by strong interactions and competitive accretion amongst protostars. Those that survive longest in the denser gas clouds without dynamical ejection become the most massive. The IMF resulting from numerical simulations of these processes resembles the Kroupa function. The first observational evidence for an accretion disk around a massive protostar was reported for an O star in M17.

- The models (and observations, e.g. of young LMC clusters) show that mass segregation occurs rapidly (\lesssim a few $\times 10^5$ yr), with the massive stars sinking to the center of dense clumps. These environments may favor stellar coagulation to form yet larger objects. The implication is that kinematical observations of even young clusters are affected by “primordial” mass segregation, leading to possible underestimates of cluster masses.
- The star formation efficiency (fraction of original cloud mass converted to stars) is ~ 10 –20% in the simulations.
- There is strong local feedback to the gas from ionization, stellar winds, stellar jets, and supernovae, but this is not well characterized yet and was not included in most models discussed. Since lower-mass stars have long pre-main sequence lifetimes of $\gtrsim 20$ Myr, they are vulnerable to feedback predations from their neighbors as long as they remain in the dense parts of the cluster. The process that terminates star formation in proto-SSC’s is not clear. However, star formation efficiencies $\gtrsim 10\%$ provide resistance to feedback and will probably produce a bound cluster.
- It was argued that magnetic fields have only a small influence on star formation compared to supersonic turbulence. This is a major departure from earlier generations of models.
- Massive stars and massive clusters are both natural products of the kinds of hierarchical models discussed. Special conditions are not required to generate SSC’s, and these appear naturally as the upper end of the mass function is stochastically populated in larger molecular cloud complexes (a “size of sample effect”).
- The major exceptions to this “uniformitarian” picture are those cases (notably NGC 1569 and 1705) where the cluster mass function is discontinuous and the SSC’s are much more massive than other clusters. A special formation mode probably operates in such circumstances, but the conditions that sustain it are not yet clear.
- Good progress is being made in analyzing Pop II and Pop III star and cluster formation in the early universe ($z \gtrsim 5$). These studies are informed by the work discussed above on nearby systems. In some ways, the situation is simpler since there are fewer free parameters (e.g. fewer complications from pre-existing structures). However, it is critical to follow radiative cooling from H_2 and the rapidly changing complement of metals in full detail. Large scale HST/ACS surveys of classical globular cluster systems (e.g. Virgo) are quickly increasing the empirical test bed for such models. The multiple subsystems of globulars revealed by HST observations are key avenues for understanding elliptical galaxy assembly.

5. Galaxy Evolution

Perhaps the overriding influence of SSC’s on our view of galaxy evolution has been to help dispel the classical picture that galaxy and globular cluster formation were confined to a unique epoch within ~ 1 Gyr of the Big Bang. We now

recognize that these are continuing, hierarchical processes, extended in time to the present epoch and strongly dependent on environment.

Massive, compact clusters are now employed as one of the best tracers of the star formation history of other galaxies. As luminous, coeval systems, they are readily identified (with sufficient resolution) and relatively easy to age-date from broad-band colors. They are especially useful for diagnosing intense episodes of star formation induced by mergers and other dynamical interactions. Cluster age statistics can isolate starburst events in time (with a precision of $\sim \pm 0.2$ – 0.3 in $\log t$) and trace the propagation of recent star formation across the faces of galaxies. More continuous, long-term star formation in galaxies can also be followed with cluster statistics, as long as the important destruction mechanisms and selection effects associated with cluster aging are taken into account.

Compact cluster destruction processes are well understood over long time-scales ($\gtrsim 100$ Myr). The main mechanisms are evaporation from two-body relaxation (for lower mass clusters) and gravitational shocking by the bulge or disk of the host galaxy. For more massive clusters, the slope of the mass function is preserved. The enormous statistical samples available in the case of systems like NGC 4038-9, however, point to other important mechanisms on short timescales. The data show that roughly 90% of the youngest clusters must be destroyed (or at least drop below the surface brightness detection threshold) over $\lesssim 50$ Myr. The same kind of “infant mortality” prevails among young clusters in the Milky Way. Early gas loss through stellar feedback, which can unbind a cluster if its star-forming efficiency was too low, is a likely driver, though the situation is not well understood.

SSC’s can play a major role in modifying the interstellar medium of galaxies. For up to ~ 50 Myr, the stellar winds, supernovae, and ionization from an individual massive compact cluster can have drastic effects on the local ISM (on display in nearby systems like 30 Dor). The crossing time for a composite cluster wind can be short enough (~ 1000 years) that X-ray observations, for instance, reflect contemporaneous internal conditions. Young cluster winds will often be enshrouded by dust, but near-IR spectral features such as the Brackett lines have permitted detection of winds and diagnosis of their properties in the emission line clusters of NGC 4038-9.

In extreme environments such as the starburst core of M82, where cluster separations may be only 2 – $5\times$ their diameters, SSC’s will act *collectively* to re-shape the global ISM of a galaxy. They can drive galactic-scale winds, entraining large amounts of external ISM material. Outflows have now been identified on small (the Milky Way center, the NGC 4038-9 ELC’s), medium (blue compact galaxies and dwarf galaxies), and large (M82, ULIRG’s) scales. In the case of M82, for instance, the cluster winds have self-collimated to produce the famous minor-axis gas plume.

One of the most interesting species of SSC’s are the nuclear clusters found in a large fraction of all late-type (Scd–Sm) disk galaxies. The nearest is in M33. These have sizes and structures typical of SSC’s (much smaller than E galaxy cores). Unlike SSC’s, they contain multiple generations of stars, indicative of approximately continuous gas transfer from the disk. Their origin and evolution are not well understood. Nuclear clusters in dwarf ellipticals may become “ultra-compact dwarf galaxies” if stripped from their parents during an encounter and

could also be mistaken for normal globular clusters (as possibly is the case for ω Cen).

One potential SSC formation environment not discussed at the conference is the high pressure cooling flow region often found at the center of X-ray clusters of galaxies. There is much evidence for star formation there, some of it induced by radio lobe/hot gas interactions. The presence of blue SSC's up to 60 kpc from NGC 1275 suggests that it might be worthwhile to re-examine cooling flow formation mechanisms.

A final important aspect of SSC's in galaxies is the possibility that they are conducive to the formation of very massive stars and/or intermediate mass black holes. Numerical models are beginning to explore the conditions necessary to generate massive objects by coagulation following mass segregation in protocluster cores. It will be interesting to see if SSC's are plausible breeders of gamma ray burst progenitors or might generate the seeds for the supermassive black holes now recognized to be intimately linked to the evolution of galaxy bulges.

6. Conclusion

There has been extraordinary progress during the last ten years in our observational and theoretical understanding of massive star clusters. This field will no doubt continue to prosper even after its observational mainstay, the Hubble Space Telescope, is retired. However, the focus will probably shift to the earliest phases of cluster formation and evolution as revealed through infrared and radio/mm observations. It may well merge with the concerted attack on the fundamentals of star formation, which has just begun and for which the prospects over the next ten years are exceptionally bright.

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